General Training On Methodologies For Geological Disposal in North America

IAEA Network of Centers of Excellence

The Yucca Mountain Project – The "Natural" and the "Man-Made" Natural Barriers"

Presented at:

Lawrence Berkeley National Laboratory, Berkeley, CA USA

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Outline

- The Yucca Mountain Project Overview
- Virtual Tour of Yucca Mountain, Nevada
- Site Evaluation and Scientific Investigations
  - What has been done?
  - What lessons have we learnt?
- The "man-made natural barriers"-capillary barrier and shadow zone
- Needs for Enhanced Basic Research to Support Yucca Mountain evaluation, EM Site Clean-Up, ...

Why Yucca Mountain?

Yucca Mountain is remote from population centers (located about 100 miles northwest of Las Vegas).

Yucca Mountain has changed little over the last million years and provides a stable geologic environment.

Yucca Mountain is located on federal land at the edge of the nation's nuclear-weapons test site (over 900 nuclear bomb tests were conducted).

Yucca Mountain has a very deep water table, among the deepest in the world, at about 2,000 feet beneath the crest of Yucca Mountain.

Yucca Mountain has a desert climate, with very low precipitation.

Site Characterization Activities at Yucca Mountain

- The initial step in determining the sites suitability is Site Characterization
- The Site Characterization Program for Yucca Mountain was initiated by the DOE in 1989 and included:

Surface-based Testing and Investigations

Underground Testing

Laboratory Studies

Modeling Activities for Evaluating Repository Performance

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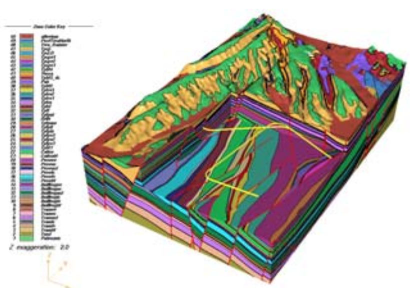
Exploring the Subsurface at Yucca Mountain



With the Exploratory Studies Facility (ESF) main loop and an additional tunnel, the Enhanced Characterization of the Repository Block (ECRB) Cross Drift, excavated in 1994-97 and 1997-98.

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Road Map for Virtual Tour of Yucca Mountain

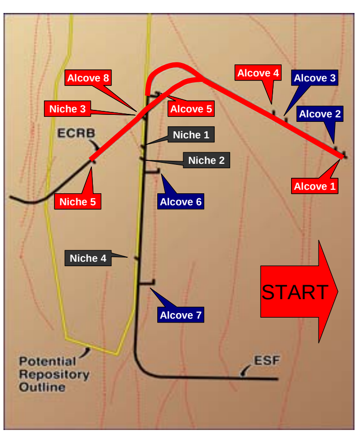
Alcove 1-Infiltration Testing

Alcove 4-Fault Testing

Alcove 8/Niche 3-Cross-Over Test

Niche 5-Seepage Testing

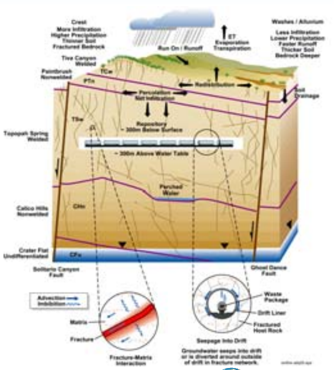
Alcove 5-Heater Testing



Begin Tour

Key Site Evaluation Activities

- Geology and Geophysics
- Fracture/Matrix Properties
- Ambient Infiltration and Percolation
- Geochemical Information and Perched Water
- Seepage into Drifts
- Transport to Water Table
- Faults as Potential Fast Pathways
- Drift Shadow Effect
- Coupled Processes (TH, THC, THM)



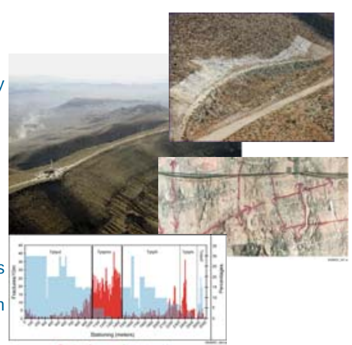
Geological Studies

Studies:

- Extensive surface mapping and trench studies
- Stratigraphy of tuff layers by over 60 deep boreholes
- Detailed line and full periphery maps of fractures on drift walls

Lessons Learnt:

- Water flow is associated with faults and a small fraction of fractures
- Detailed fracture mapping is useful mainly for fracture-matrix interaction evaluation



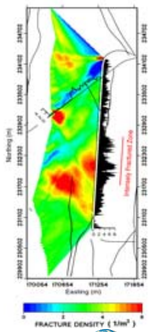
Geophysics Studies

Studies:

- Electromagnetic (EM) imaging
- Seismic imaging (large scale)

Lessons Learnt:

- EM of limited use due to difficulty to inject current into ground
- Surface to underground seismic imaging identified intensively fracture zones
- All geophysical tools need improvements to detect large hydrological features: perched water bodies, hidden faults



Water Flow Evaluation
– Infiltration

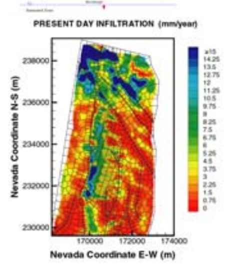
Studies:

Meteorological stations to measure precipitations and evaporation-transpiration potentials

- Neutron logging of hundreds of shallow boreholes
- Stream gauges to monitor channel runoff
- Water bucket models for wetting front migration

Lessons Learnt:

- Difficult to estimate infiltration with conventional approach (above)
- Essential to use geochemical and thermal data to support and constraint the model



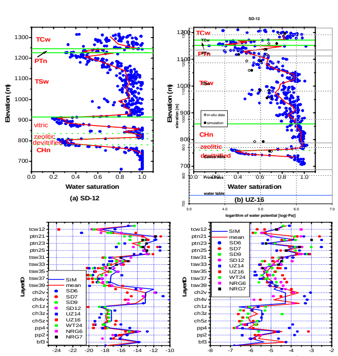
Water Flow Evaluation
– Matrix Properties

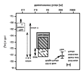
Studies:

- Saturation and water potential measurements on cores and in boreholes
- Upscaling achieved by inverse modeling

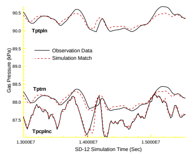
Lessons Learnt:

- Water potential is extremely difficult to measure in the range of 0 to –5 bar (may not be important)
- Practically impossible to separate effects of fractures in borehole measurements
- Core drying affects saturation data





Water Flow Evaluation
– Fracture Properties



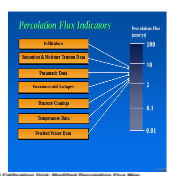
Studies:

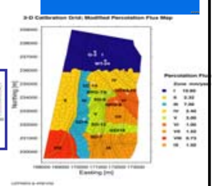
- Air permeability (K) measured by packer tests (0.3 to 10 m)
- 100 m scale air-K inferred from pneumatic data (damping of atmospheric pressure signals)
- Fracture porosity determined by gas tracer tests and inferred from inverse modeling of seepage and thermal test data

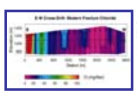
Lessons Learnt:

- Pneumatic data extremely useful – confirming theoretical upscaling power law (and no air-K upscaling is needed in YM evaluation)
- Fracture porosity is on the order of 0.5% - similar to other rocks

Water Flow Evaluation
– Percolation







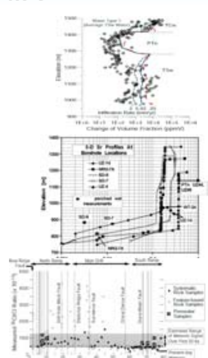
Studies:

- Site-Scale Model, matched with all available data, is used to determine percolation from redistribution of infiltration
- In addition to hydrological and pneumatic data, temperature and geochemical data (especially total chloride) are used to constraint both flux magnitude and spatial distribution

Lessons Learnt:

- Total chloride and temperature data provide most useful constraints for both magnitude and distribution

Water Flow Evaluation
– Geochemical Information



Studies:

- Porewater samples are collected from squeeze and ultracentrifuge
- Gas and perched water samples are collected from pumping
- Systematic and feature-based samples are collected for bomb pulse analyses

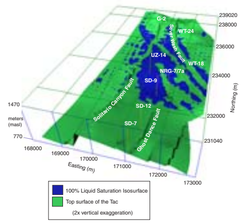
Lessons Learnt:

- Total chloride, calcite, Sr, Cl^{36} are very useful to elucidate different flow phenomena
- Controversy persists on bomb pulse finding (may not be important)

Water Flow Evaluation
– Perched Water

Studies:
- Pump testing to determine the spatial extent
- Water sampling to determine ages and chemical mixing

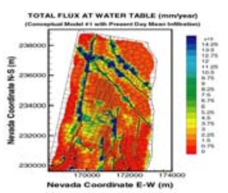
Lessons Learnt:
- Existence of perched water bodies infers that fracture permeability below perched water is low
- Partial diversion minimizes contact with zeolitic tuff with strong sorbing capacities
- Model results suggest flow focusing and channeling to faults

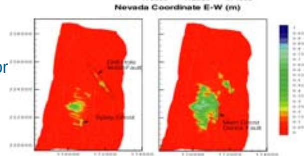


Water Flow Evaluation
– Flow Pattern Below Repository

Studies:
- Use information from limited number of deep boreholes
- Site-scale flow model is used to evaluate flow pattern

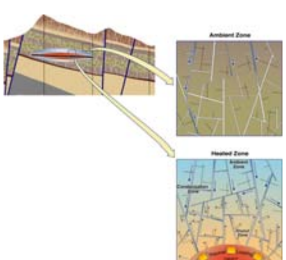
Lessons Learnt:
- Lack of data makes the large-scale geological layer structure and features very important
- Modeling results suggest significant diversion to the faults for percolation and radionuclide transport





Fracture-Matrix Interaction
- Conceptual Model

Studies:
- Use double-porosity, dual-permeability, multiple-interacting continuum, and discrete fracture models to evaluate the fracture-matrix interaction
- Formulate the active fracture model to represent the transition from weak interaction at low fracture saturation (ambient condition) to high saturation (in the condensation zone)

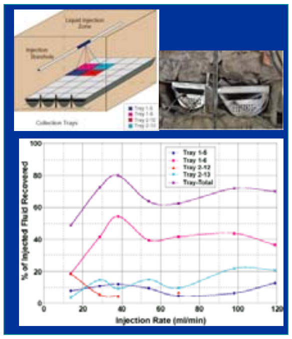


Lessons Learnt:
- Transport is more sensitive than flow to the F/M and active fracture representation
- Condensate imbibition into matrix block is better understood than drainage

Fracture-Matrix Interaction
- Alcove 6 Test

Studies:
- Use a slot excavated below the test block to collect water flowing through fractures
- Use different tracers to evaluate the effectiveness of piston-flow behavior along flowing fractures

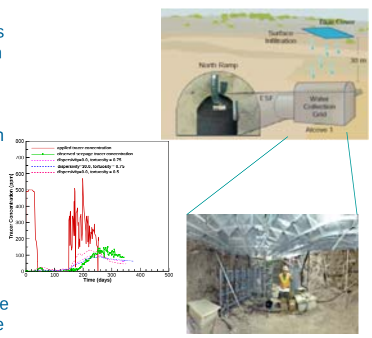
Lessons Learnt:
- Up to 80% of injected water flows through discrete fracture paths
- Outflows occurred in step increments which could be related to water stored in fracture flow paths
- Strong matrix imbibition and weak migration out of matrix were observed



Solute Transport
- Alcove 1 Infiltration Study on the Bedrock

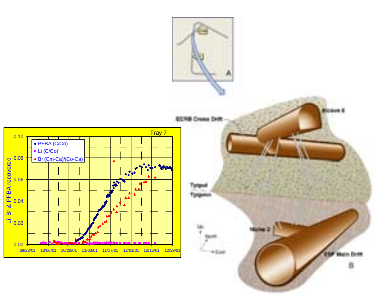
Studies:
- Apply hips infiltration rates below run-off threshold on the ground surface
- Collect seepage at Alcove 1, 30m below, for water and tracer collection

Lessons Learnt:
- Matrix diffusion is important in order to interpret delay in tracer breakthrough
- Infiltration is controlled by near surface layer with permeability lower than the fractured rocks around the alcove



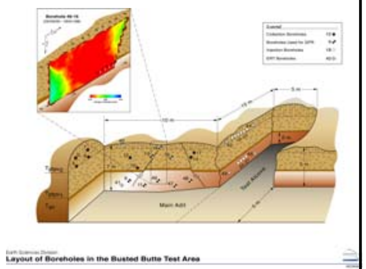
Solute Transport
- Alcove 8/Niche 3 Fault Test

- Studies:
- Infiltrate water along a fault at Alcove 8 in the ECRB Cross Drift, and collect seepage in Niche 3 in the ESF Main Drift, ~20 m below
- Inject two tracers with different sizes to evaluate matrix diffusion effects
- Lessons Learnt:
- First arrival was along the fault, with subsequent seepage also through fracture network
- Clear observation of matrix diffusion dependence on tracer size, with large molecules staying more in the fractures



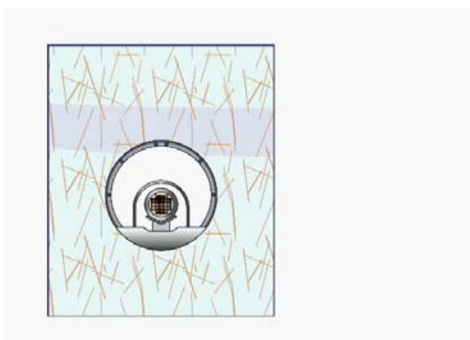
Solute Transport
- Busted Butte Transport Test

Studies:
- Inject multi-tracer solutions into borehole arrays in and above Calico Hills vitric tuff
- Track plume migrations with periodic Ground Penetrating Radar imaging between borehole pairs



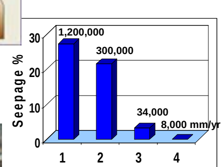
Lessons Learnt:
- Calico Hills vitric tuff has simple porous medium characteristics with well-defined plume pattern
- Different tomographic techniques are useful to monitor plume migration

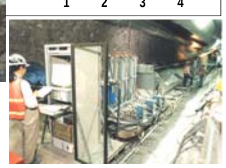
Capillary Barrier and Shadow Zone



Seepage Evaluation
– *Testing*

Studies:
- Seepage tests with liquid releases directly above niches
- Systematic testing in ventilated Cross Drift sections with large cavities
- Seepage and condensate observations in kilometer long sections behind bulkheads

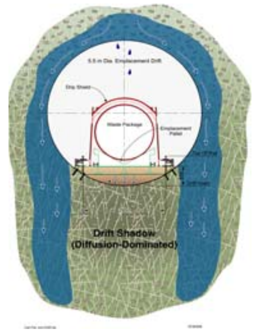




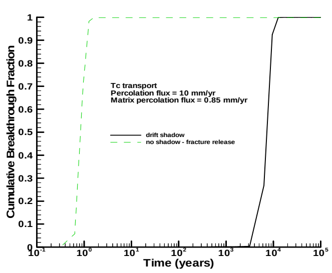
Lessons Learnt:
- Capillary barrier effects result in a seepage threshold (no seep below ~ 1000 mm/yr, as compared to percolation of ~ 5 mm/yr)
- Majority of repository rock with large cavities have even higher thresholds
- Long term tests in closed tunnels have shown no seepage so far

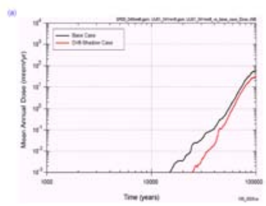
Drift Shadow Concept

- Drift Shadow (zone of lower water saturation and flux) from seepage diversion is expected to exist in 50 to 90% of drifts
- Radionuclides primarily enter the rock matrix by diffusion



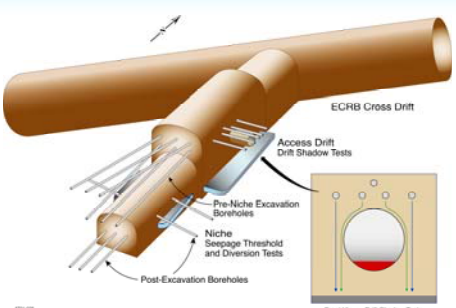
Impact on Radionuclide Transport - Ambient Conditions





- Transport times of thousands of years calculated, compared with a few years for release into the unperturbed flow

Validation by Testing

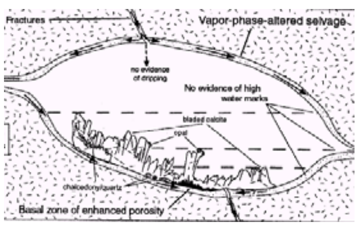


- Measure if diverted or introduced water picks up dry tracers emplaced at the bottom of the drift

Validation by Analogue

- Determine if bomb pulse signals are detected mainly above old mine drifts

Validation by Cavity Modeling

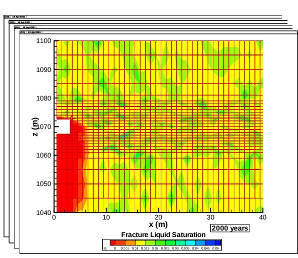


Shadow zone -
reduced transport capacity

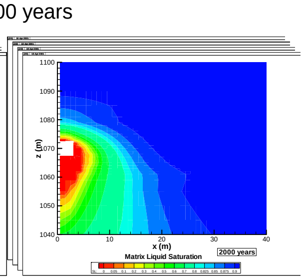
- Deposition patterns on the bottom of lithophysal cavities may be due to the relatively low transport capacity below excavation.

Impact on Radionuclide Transport - Thermal Effects

t = 2000 years



Fracture Saturation

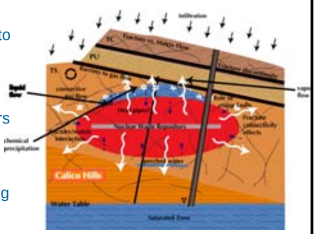


Matrix Saturation

- Additional thousands of year delays from thermal dryout (SSPA)

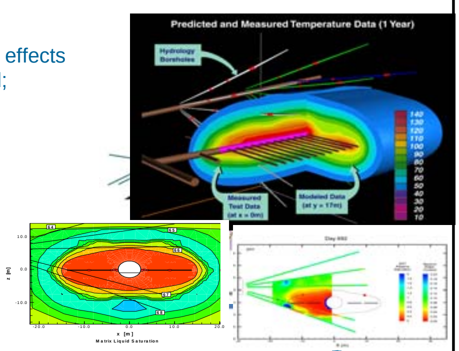
Thermally Driven Coupled Processes

- When nuclear waste is emplaced into the drifts at Yucca Mountain, heat radiating from the canisters into the surrounding rock will elevate temperatures and trigger thermally driven processes.
  - Vaporization of interstitial waters
  - Dissolution and precipitation of minerals
  - Stress-induced movement along fractures
- Collaborative effort by LANL/LBNL, LLNL, and SNL



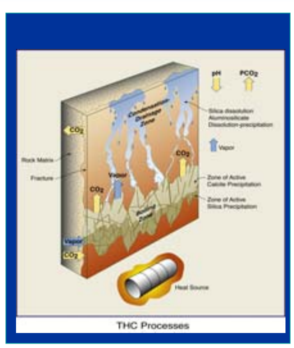
Waste Heat Induced Coupled Processes (Thermo, Hydrologic, Chemical, Mechanical)

- TH heat pipe effects are observed; THC/THM mechanisms identified



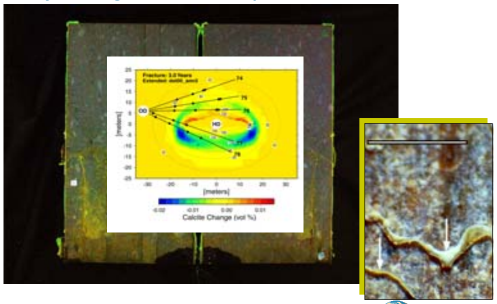
THC Coupled Processes

- Reaction rates
  - Generally increase with elevated temperatures
- pH affected by
  - CO_2 degassing and transport
- Chemical evolution of waters, gases and minerals intimately coupled to TH processes
  - Drying concentrates aqueous species in remaining liquid phase
  - Pure water in condensation zones promotes dissolution of minerals
- Mineral dissolution and precipitation
  - Changes porosity and permeability
  - Affects seepage into drifts
  - Alters chemistry of water that could contact waste package



Waste Heat Induced Coupled Processes (T, H, C, M)

- Thermo-hydrologic-chemical processes



Key Scientific Questions

- **Fluid Flow Patterns – averaged steady percolation or focused discrete pulses ?**
- **Drift Shadow Zone performance – radionuclide released into slow matrix or flowing through fractures?**
- **Coupled Processes and waste loading – thermal barrier within compact repository vs. uncertainty reduction in below boiling performance?**
- **Radionuclide Transport properties – up scaling from crushed tuff results and confinement over geological time scales?**

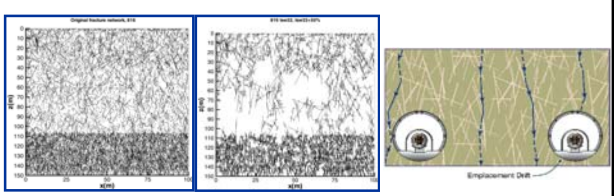
Vadose Zone Flow Pattern

Current Understanding:

- Dispersive and continuous flowpaths in many fractures and modest flow focusing to yield 50% of drifts with seepage
- Active fracture model is used to represent averaged number of flow fractures and effective fracture/matrix interaction area

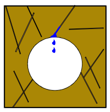
More Likely Pattern:

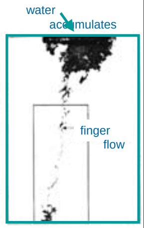
- Practically 1D flow tubes with spacing of ~10 m



Yucca Mountain Science and Technology Program

- Committed by Dr. Margaret Chu, Director of OCRWM
- Should support detailed fracture flow experiments to address global flow and transport issues
- Should support applied research into complex vadose zone issues
- Should support integrated hydrological, geochemical, and geophysical evaluations of all existing data to infer possible water flow patterns





Summary

- Very comprehensive site characterization of Yucca Mountain conducted using boreholes and underground tunnels
- Geological, geophysical, geochemical, and hydrological studies have yielded great insights into global flow and transport at the site
- The main natural barriers in the unsaturated zone at Yucca Mountain are the “man-made” barriers due to capillary diversion around drifts and “shadow-zone” effects